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Running head: DELAYED AUDITORY FEEDBACK DURING CRYING BOUTS

Effects of Delayed Auditory Feedback on Young Infants' Crying

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Master of Arts Thesis

Effects of Delayed Auditory Feedback on Young Infants' Crying

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Table of Contents

Abstract	iv
List of Figures	v
List of Tables	vi
Introduction	1
Delayed Auditory Feedback Effects on Speech and Crying	2
Neurophysiological Models of Cry Production	6
Age Trends in Cry Acoustics	11
Rationale for Present Study	15
Method	16
Participants	16
Materials	16
Procedure	17
Analyses	18
Results	19
Simple ANOVA Results for Cry Sounds	19
Multilevel Modeling of Cry Sounds	20
Summary of Results	23
Infant Behavior Questionnaire Soothability Subscale	24
Summary of IBQ Correlations	25
Discussion	26
References	34
Figures	43
Tables	48

Abstract

Neural control of newborn crying has typically been considered to originate primarily in the lower brain centers, although support for this assumption is limited. To address this, the present study manipulated newborn infants' perceptual experience during a cry bout through use of delayed auditory feedback (DAF). Atypical cry productions during DAF would suggest that newborn crying is under higher levels of cortical control than previously assumed. Infants' spontaneous crying was recorded for 2 minutes at 4 weeks of age ($n=16$) and again at 8 weeks of age ($n=17$) using an ABA design, alternating synchronous feedback with DAF. Standard repeated-measures 2 (age) x 3 (condition) ANOVAs found DAF effects for mean proportion of energy in the lower frequency bands and its variability and an interaction effect for variability in cry duration. Multilevel modeling, however, revealed several more DAF effects, again for mean proportion of energy in the lower frequency bands, but also for other acoustic variables such as maximum frequency, duration, and variability in the mean F_0 . Future research using DAF or other manipulations is needed to further clarify the neurophysiological processes that control newborn cry production and to examine the links between early cry production and later developmental outcomes.

List of Figures

Figure 1. Age effects on mean energy in cry sounds.....	43
Figure 2. Age effects on mean cry duration.....	43
Figure 3. DAF effects on mean proportion of energy in the 100-500 Hz band.....	44
Figure 4. DAF effects on mean proportion of energy in the 500-1,000 Hz band.....	44
Figure 5. DAF effects on mean proportion of energy in 1,500-2,000 Hz band.....	45
Figure 6. DAF effects on mean maximum frequency of cry sounds.....	45
Figure 7. DAF effects on mean energy in cry sounds.....	46
Figure 8. DAF effects on mean cry duration	46
Figure 9. DAF effects on mean variability in cry mean F_0 (Hz).....	47

List of Tables

Table 1. Definitions of Acoustic Measures.....	48
Table 2. Intra-class Correlations (ICCs) for MLM models on Cry Sounds.....	49
Table 3. Condition Effects from Multilevel Modeling Analyses	50
Table 4. Estimated Marginal Means (SEs) by Condition at 4 and 8 Week Visits	51
Table 5. Simple ANOVA analyses compared to MLM analyses for Cry Sounds.....	53
Table 6. Correlations between Soothability Scores and Acoustic Variables.....	54

Effects of Delayed Auditory Feedback on Young Infants' Crying

Crying among newborn infants should be regarded as a “complex, dynamic feedback system” (Lester, 1985, p. 12); as infants produce cries through the coordination of laryngeal and respiratory muscles, they simultaneously receive auditory and kinesthetic feedback. In other words, crying is a “movement made audible” (Hopkins, 2000, p.182). Much research has focused on newborn cry production or adult perception of newborn cry sounds, but little research addresses how the newborn, as the producer and perceiver of its own cry sounds, might experience the cry bout.

Newborn cries have typically been considered reflexive, driven by the respiratory system and cranial nerves, although direct tests of this assumption are limited. One way to consider the influence of higher brain areas would be to manipulate infants' perceptual experience during a cry bout, for example, with delayed auditory feedback (DAF). Atypical cry production under conditions of DAF would suggest that crying is more than a simple reflex. Indeed, it is possible that the perception-action coupling that infants receive during cry bouts may facilitate later language development, a link made in a few previous studies that used early cry acoustics to predict later developmental outcomes (i.e., Karelitz, Fisichelli, Costa, Karelitz, & Rosenfeld, 1964; Lester, 1987; Wermke, Leising & Stellzig-Eisenhauer, 2007). The purpose of the present study is to examine whether and how newborn crying is disrupted under conditions of DAF. If newborn crying is under greater cortical control, acoustic features influenced by glottal muscles, such as mean fundamental frequency (F_0) and its variability, along with acoustic features influenced by supraglottal muscles, such as energy in selected frequency bands, should be most affected during conditions of DAF.

Delayed Auditory Feedback Effects on Speech and Crying

Speech is a complex act involving coordination and execution of specific muscles in the vocal tract, during which the auditory feedback must be processed. There are disagreements in the literature as to whether or not vocalizations operate under a closed-loop auditory feedback system before language develops.

Vocal productions should be measurably affected by an unexpected change in auditory feedback if a closed-loop auditory feedback system is in place. DAF has been used in several studies to examine the role of auditory feedback during speech and non-speech vocalizations. DAF has also been incorporated in speech therapy for individuals with severe stuttering, as it trains them to become less reliant on auditory feedback and more focused on the motor movements involved in producing speech (Ryan & Van Kirk, 1974; Van Borsel, Reunes, & Van den Bergh, 2003).

In the adult literature, DAF during speech typically results in more speech errors, increases in sound pressure, and slower rates of speech (Fairbanks, 1955; Yates, 1963). However, results are not as straightforward among studies with children or infants, making it difficult to speculate about the neurological processes involved in early and later speech production. Chase, Sutton, First, and Zubin (1961) showed DAF to be more disruptive to speech among 7- to 9-year old children when compared to 4- to 6-year-old children. In a study conducted by Yeni-Komshian, Chase, and Mobley (1968), DAF affected vocalizations made by the older children (28-35 months) significantly more than the younger children (21-26 months). Belmore, Kewley-Port, Mobley, and Goodman (1973) demonstrated that DAF effects were most consistent among the older infants (12-19 months), in that duration and peak sound pressure level increased under DAF, while

DAF effects were less consistent, but generally measurable, among younger infants (6-10 months). Furthermore, Belmore et al. (1973) found that the children affected most by DAF were more linguistically advanced in the sample, suggesting that reliance on auditory feedback enhances speech production, which is line with the results from Chase et al. (1961) and Yeni-Komshian et al. (1968).

In contrast to these previous results, MacKay (1968) found higher rates of speech interference during DAF among younger children (4-6 years) compared to older children (7-9 years) and adults (20-26 years). They also found that longer delay periods increased speech errors among the youngest children. Further, DAF effects were most pronounced among those with slower speech rates, which were more prevalent among younger ages (4 to 9 years). Ratner, Gawronski and Rice (1964) found more speech errors during DAF among younger children (6-10 years) compared to older children (12-13 years), but only when exposed to several trials of DAF, as there were no age differences in speech errors after the participants' initial exposure to DAF. Such discrepancies in the literature may be at least partially reconciled if children were grouped by language level rather than age and if methodologies between studies were more consistent (Belmore et al., 1973).

The idea that linguistically advanced speakers would be less reliant on auditory feedback with experience is supported by much of the stuttering research. This research shows that DAF facilitates speech fluency for stutterers (Chase, Sutton, & Rapin, 1961; Soderberg, 1969). In fact, DAF is used frequently in speech therapy to reduce stuttering in patients (Ryan and Van Kirk, 1974; Van Borsel et al., 2003). Thus, it seems that the role of auditory feedback in speech production is not entirely understood at this point. Are individuals more or less reliant on auditory feedback as they gain experience using

their own language? Although much of this research acknowledges the large variability in responses to DAF, these studies rely on group-level responses to DAF, ignoring individual-level data, which may explain the discrepancies observed in the field, at least to some degree, as it is possible that auditory feedback reliance is highly variable within individuals and does not necessarily follow a linear increase over development.

Do prelinguistic infants rely on auditory feedback when producing non-speech vocalizations, such as crying, fussing, and babbling? In order to address this question, Cullen, Fargo, Chase, and Baker (1968) measured changes in newborn infants' cry duration, maximum sound pressure level, and cry pause time during periods of synchronous and delayed auditory feedback (200 msec). Ten infants (aged 1-7 days) were tested twice in the order of synchronous feedback followed by delayed feedback, and 6 infants were tested twice in the reverse order. Results showed some DAF effects, including a decrease in cry duration during DAF, regardless of test-order, and a decrease in amplitude during DAF, but this effect was only for infants tested in the DAF-synchronous order. The lack of acoustic parameters gathered during this study, along with the order effects observed, makes it uncertain as to whether or not DAF effects are very robust in newborns.

Animal models can be used to illustrate the role of auditory feedback in the absence of language, and such results could yield a better understanding of the role of auditory feedback in non-linguistic vocalizations, such as infant cry production. Cynx and Von Rad (2001) found DAF effects during songs produced by zebra finches, with effects such as increased amplitude of the bird songs and more variation in songs (consisting of changed syllable order, perseverated or more introductory notes,

incomplete songs, and starting songs in novel places) when compared to songs produced during simultaneous auditory feedback. Auditory feedback has also been shown to affect kittens, whose calls grow louder as white noise levels increased through a pair of headphones fitted to their ears (Buchwald & Shipley, 1985; Shipley, Buchwald, Carterette, & Strecker, 1981). Moreover, kittens deafened at 2-4 weeks produce distress calls that are shorter in duration, louder, and have less stable fundamental frequencies compared to age-matched controls (Buchwald & Shipley, 1985; Shipley et al., 1981). Buchwald and Brown (1977) found that the formant frequencies of distress calls were affected when 4-week-old kittens were deafened, but fundamental frequency (F_0) was not affected.

Eliades and Wang (2008) showed that activity in the auditory cortex of marmoset monkeys was suppressed when receiving real-time feedback while vocalizing, but neural activity increased when the pitch of their vocalizations was altered. Similarly, neural activity is suppressed during self-produced speech in humans, when compared to hearing altered real-time feedback or listening to a recording of one's own speech (Curio, Neuloh, Numminen, Jousmaki, & Hari, 2000; Houde, Nagarajan, Sekihara, & Merzenich, 2002). Thus, vocalizations made from non-human species described above seem to rely on real-time unaltered feedback, suggesting that auditory feedback is necessary for any type of vocalization, speech or non-speech.

We can learn more about the role of auditory feedback on non-speech vocalizations by analyzing the cry sounds produced from congenitally deaf infants, who receive little to no auditory feedback during cry bouts but still experience the physiological feedback that typically accompanies cry bouts. Although the amount of

research in this particular area is limited, results stemming from these studies seem promising regarding the influence of auditory feedback on cry sounds. First of all, experienced listeners rated cry sounds from profoundly hearing-impaired infants (3-12 months) as weak, flat, and more guttural in comparison to hearing infants (1-10 months; Möller & Schönweiler, 1999). Furthermore, acoustic analyses have characterized the cry sounds from hearing-impaired infants as having less energy in upper frequency bands and being more melodically complex and longer in duration than cry sounds from hearing infants (Möller & Schönweiler, 1999). Scheiner, Hammerschmidt, Jürgens, & Zwirner (2004) audio-recorded various sound types (crying, fussing, laughing, cooing, and babbling) from hearing-impaired and hearing infants 6-8 times throughout their first year; cry sounds were structurally different between groups, but no other sound types were different, including babbling, perhaps because babbling emerges later in development with respect to crying. Supporting Möller and Schönweiler (1999), Scheiner et al. (2004) showed that hearing-impaired infants had cry sounds with longer durations, less energy in upper frequency bands, and more melodically complex cries, as well as cry sounds reaching a higher maximum F_0 and an earlier onset of maximum frequency within the F_0 .

Neurophysiological Models of Cry Production

A handful of studies have used differences in cry sounds to predict later cognitive or language development (Karelitz et al., 1964; Lester, 1987; Mampe, Friederici, Christophe, & Wermke, 2009; Wermke et al., 2007), but these studies presume newborn cry sounds to be controlled by higher brain processes, rather than respiratory and lower brain systems. Thus, it is worthwhile to consider theoretical models of cry production, as offered by Golub (1980), Lester and Zeskind (1982), and Porges, Doussard-Roosevelt,

and Maiti (1994), all of which suggest that cry acoustics, as well as the latency and duration of cry bouts, are initiated and shaped by various components of the nervous system. These neurophysiological models of cry production have been developed, in part, to explain the high degree of variability observed in newborn infant cry sounds, especially among atypical or at-risk populations (for review, see Green, Irwin, and Gustafson, 2000).

Golub (1980) developed a cry production model to facilitate the diagnoses of specific pathological conditions based on acoustic parameters of newborn cry sounds. According to Golub (1980; Golub & Corwin, 1985), newborn cry sounds are initiated by upper and middle level processors of the central nervous system (CNS), but acoustic characteristics of such cries are shaped by lower level CNS processing, which independently control subglottal (respiratory), glottal (larynx), and supraglottal (vocal and nasal tract) muscles. Through extensive testing, Golub proposed that specific abnormal cry characteristics could be linked to each of these three muscle groups. Thus, specific acoustic characteristics of cry sounds, such as glottal instability or abnormal respiratory effort, can be used to diagnose infants with specific CNS deficits. For example, the vagus (the 10th cranial nerve) controls the movement of the glottal muscles, which affects the fundamental frequency (F_0) of the cry, while other parts of the CNS control subglottal or respiratory muscles, which affect the energy and duration of the cry (Golub, 1980; Green et al., 2000). However, the assumption that these muscle groups are independently controlled is not supported in cry research, particularly when measuring spontaneous cry sounds, rather than pain-induced cry sounds, and when analyzing changes in the cry sounds over the duration of a cry bout (Green, Gustafson, & McGhie,

1998; Green et al., 2000). Regardless, the primary notion of Golub's model revolves around the understanding that cry sounds can be used to reflect early CNS functioning, but are not under a great deal of higher-level cortical control.

Rather than focusing on the role of the CNS, Lester & Zeskind (1982) propose that the autonomic nervous system (ANS) plays a large influence on the initiation and latency of cry bouts as well as the acoustic characteristics from the cry bouts. In particular, Lester and Zeskind (1982) focus on two distinct parts within the ANS: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). When the infants' environment (internal or external) changes, the SNS excites the system, initiating the cry signal. In response to SNS excitation, the PNS inhibits the infants' responses to the environment through the vagus, a cranial nerve that sends information to and from different organs within the body and controls the laryngeal muscles involved in cry production. Cry latency and duration can be used as measures of SNS functioning, while cry acoustics, particularly fundamental frequency and dysphonation, can be used as measures of PNS function. Similar to Golub's (1980) model, Lester and Zeskind's (1982) biobehavioral model relies on the opposition between the SNS and PNS to characterize nervous system functioning in the newborn, given the qualities of the cry bout.

Porges et al. (1994) focus on the influence of the vagus system (which affects digestion, respiration, emotion, and communication) on emotional expression. According to this model, physiological changes in the body experienced as a result of an emotional response to an internal or external source are due to the influence of the vagal system, which controls heart rate, respiration, and laryngeal muscles. Vagal tone, a measurement

of heart rate variability, has been correlated with later developmental outcomes among newborns in areas of cognition, attention, and emotion-regulation (Porges et al., 1994; Porges, Doussard-Roosevelt, Portales, & Greenspan, 1996; Doussard-Roosevelt, Porges, Scanlon, Alemi, & Scanlon, 1997).

However, only a small portion of the Porges et al. (1994) model addresses the neurophysiological influences of the vagus system on cry production. The model proposed that acoustic qualities of cry sounds change according to control afforded by the laryngeal muscles, which are regulated by the vagus (Porges et al., 1994; Green et al., 2000). High-pitched and unstable cries, landmark characteristics of pathological and pain cries, are explained in this model as a result of the contraction and relaxation of the laryngeal muscles, given the degree of stimulation received from the vagus nerve fibers (Porges et al., 1994; Green et al., 2000).

All cry production models focus on the role of the nervous system in stimulating cries and shaping cry acoustics, however, the specific acoustic characteristics associated with specific nervous system functioning remains unclear. Newborn infants with CNS deficits have qualitatively different sounding cries, defined by higher-pitched, shorter duration, and more variable cries (Corwin, Lester, & Golub, 1996; Lester and Zeskind, 1982; Porter, Porges, & Marshall, 1988; Wasz-Höckert, Michelsson, & Lind, 1985). Similarly, healthy pre-term infants produce cries that have a higher mean F_0 than full-term infants (Michelsson, 1971). The mean F_0 in infants' cries increases as their gestational age decreases, suggesting that CNS maturation affects at least some degree of cry acoustics (Michelsson, 1971). Furthermore, brain damaged infants typically produce high-pitched cries, with little variability in pitch (Michelsson, 1971; Michelsson, Sirviö,

& Wasz-Höckert, 1977). However, it is uncertain how relevant these models are as the infant develops during the first year, or even how resilient these models are throughout the duration of a single cry bout (Green et al., 1998).

Infant cries were initially conceptualized as being discrete signals for states such as hunger or pain (Wasz-Höckert, Lind, Vuorenkoski, Partanen, & Valanne, 1968); however, cries now are typically regarded as continuous, graded signals, given the adult cry perception literature (Sherman, 1927; Müller, Holien, & Murry, 1978; Gustafson and Harris, 1990; for review, see Gustafson, Wood, and Green, 2000). Treating cries as graded signals reflecting changes in underlying arousal offers challenges to Golub's (1980) model, because healthy infants, when under a great deal of distress, share some of these same cry characteristics as atypical infants, such as higher F_0 and more instances of hyperphonation (Lester & Zeskind, 1982). For example, Porter, Miller, and Marshall (1986) showed that cries from healthy newborn males undergoing circumcision had the highest and most variable F_0 values during the most invasive parts of the procedure. Furthermore, Green et al. (1998) recorded spontaneous cries from a set of healthy newborn infants and found that maximum F_0 and its variability increased as the cry bout progressed. Acoustic characteristics common for hunger cries were prevalent early in the cry bout, while acoustic features common for pain cries were prevalent later in the cry bout (Green et al., 1998).

Thus, acoustic variables such as maximum frequency, pitch, and their variability seem most related to arousability of the infant, which may help explain why premature infants with neurological disorders typically produce higher-pitched cries. The viewpoint of crying as a graded signal complements cry production models presented by Lester and

Zeskind (1982) and Porges et al. (1994), both of which attribute changes in vocal production to increasing physiological arousability within an individual.

Age Trends in Cry Acoustics

Little is known about the developmental changes in cry acoustics during the first year of life (Green et al., 2000; Hopkins, 2000). Such knowledge is needed to elucidate the links of early cry sounds to later developmental outcomes (Lester, 1987; Michelsson et al., 1977) and to understand more about the neurophysiological influences on cry acoustics that take place within the early postnatal period. Many of the longitudinal studies that have looked at changes in cry vocalizations during the first year have extremely small sample sizes, large sampling intervals, and focus on the frequency of vocalization types (cry, fuss, cooing), often collected by parent-report, rather than changes in cry acoustics (Baeck & de Souza, 2007; Green et al., 2000; Wermke & Lind, 2002). For example, Brazelton (1962), through the use of parent diaries, documented a cry peak at 6 weeks of age, however the cry peak reflected an increase in infants' cry frequency, which did not exclude less intense fuss sounds, nor did it measure total duration of cry bout (Hopkins, 2000). Hopkins and van Wulfften Palthe (1987) videotaped 14 infants between 3 to 18 weeks during mother-infant interactions and when infants were alone; increased fussing and cooing vocalizations were observed between 2-3 months, however, no acoustic analyses for any vocalizations were conducted.

During the first postnatal week, cry duration decreases (Prechtl, Theorell, Gramsbergen, & Lind, 1969), as does the number of pitch-shifts within a cry (Wasz-Höckert et al., 1968). Prescott (1975) found that cry melody becomes more variable during the first few postnatal months, and suggests that such change is due to increased

control of the vocal tract and increased lung strength. At 3 months of age, the larynx descends further down the vocal tract, allowing mouth breathing to occur and increasing the range of sounds that can be produced (Lieberman, 1985). Also, around 3 months of age, the ribcage changes from being perpendicular to the spine to being angled downward from the spine, which allows for subglottal air pressure to be better regulated (Lieberman, 1985) and greater variability in cry sounds produced (Hopkins, 2000). Between 2-3 months of age, there are transitions in the organization of the CNS (Emde, Gaensbauer, & Harmon, 1976); such a change can affect cry acoustics (Lester, 1985). More research is needed to examine the way in which these neurophysiological changes in the infant affects the acoustic quality of the cry, and in turn, the extent to which observed differences in cry acoustics can be traced to neurophysiological measures.

Rothgänger (2003) observed a significant increase in cry mean F_0 throughout the first year of life and also observed cry melody contours to first follow symmetrical patterns during the first 3 months, and then falling patterns between 4-12 postnatal months. Baeck and de Souza (2007) measured the F_0 of hunger cries from 30 infants on a biweekly basis between 0 to 6 months and found a decrease in F_0 during the first 2 postnatal weeks, suggested by the authors to reflect a change in vocal tract maturation. Cry mean F_0 increased steadily between 2 and 6 weeks, and finally stabilized between 8 and 25 postnatal weeks, during which mean F_0 values oscillated between 405-397 Hz. Overall, Baeck and de Souza (2007) reported mean F_0 values in their study to be much more variable than previously measured in the literature. There are other studies that do not find any age-related changes for cry mean F_0 . For example, Murry, Hoit-Dalgaard, and Garacco (1983) found no changes in mean F_0 from the cries of one infant at 4 and 8

weeks. Similarly, Lind and Wermke (2002) focused on changes in F_0 during spontaneous cries taken from one infant within the first 3 postnatal months, but found no significant increases in cry mean F_0 , unless they only analyzed cries lasting less than 0.8 seconds. Cries less than one second in duration are usually identified as fuss sounds, which are often analyzed separately in cry research.

Studies thus far collected on acoustic changes in cry sounds during the first year focus, for the most part, on changes in the mean F_0 ; however, the results are not in agreement, partly due to methodological differences. Inclusion of other acoustic measures, such as variability of mean F_0 , and mean and variability of energy in specific frequency bands, melody contours, dysphonation, harmonicity, and maximum and minimum frequency, should be collected and analyzed for intra-individual changes throughout the first postnatal months, especially given the fact that inter-individual variability is highest during the first 3 months of life (Barr, 1990; Hopkins, 2000).

From a systems framework, we may be able to pinpoint key periods of developmental transition if we focus more on variability measures, both within and between individual infants (Hopkins, 2000), expand our focus on limb movements that occur during cry bouts (Green et al., 2000), and obtain more neurophysiological measures during newborn cry bouts (Emde et al., 1976). During cry bouts, infants receive both auditory and physiological feedback from limb and respiratory movements; such feedback may facilitate perception-action coupling needed for later speech (Hopkins, 2000) and may explain the link of newborn crying to later developmental outcomes (Zeskind, 1985). Therefore, it is plausible that cry acoustics may change as feedback experience is increased, both during a single cry bout and throughout the first year of life.

Specific characteristics of newborn crying have been used to predict later developmental outcomes. Karelitz et al. (1964) correlated active crying (assessed by cry count) among newborn infants to higher Stanford-Binet IQ scores at age 3. Lester (1987) found that newborn infants who had higher-pitched, more variable, and lower amplitude cries had poorer developmental outcomes at 18 months (Bayley Scales) and 5 years (McCarthy Scales; includes verbal score). Wermke, Mende, Manfredi, and Brusciaglioni (2002) showed increasing melodic complexity of cries and more stable F_0 values among infants between 2 and 3 months of age and proposed that such age-related changes reflected a developing CNS. Wermke et al. (2002) hypothesized that infants with more complex cries, and thus, a matured CNS, will have optimal developmental outcomes. To support this assertion, Wermke et al. (2007) recorded cries from 2-month-old infants and assessed language abilities among the same infants at 2.5 years; infants with more melodically complex cries at 2 months yielded higher language scores at 2.5 years.

It is unclear whether the action of crying specifically contributes to later developmental outcomes, or if crying is simply an indicator of CNS function, which could be correlated to later outcomes. Although such research is not conclusive, crying does serve as an important communicative tool for infants. Parents perceive infant crying to be more intentional and communicative between 2-3 months (Boukydis, 1985; Lester & Boukydis, 1992). Infant cry bouts are increasingly accompanied with gestures and gazes to the caregiver as their age increases (Gustafson & Green, 1991). By the end of the first year, infants cry more when in sight of their caregiver (Bell & Ainsworth, 1972). Thus, crying, while not linguistically rich, does serve as an important aspect of pre-linguistic communication.

Rationale for Present Study

The primary purpose of this study is to extend the previous work on the effects of DAF on newborn crying. No study since Cullen et al. (1968) has investigated whether newborn crying can be disrupted by DAF. Further, there are a few methodological problems with this original study. First, Cullen et al. (1968) analyzed the effects of DAF on pain cries; use of DAF on spontaneous cries may yield different results, given that infants may be less responsive to auditory feedback when under conditions of pain. Second, only measures of cry and cry-pause duration and maximum sound pressure level were obtained in Cullen et al. (1968), and these measures were averaged across infants. Other acoustic measures should be considered in order to fully assess whether or not DAF might affect newborn cry bouts. Also, individual-level responses to DAF should be considered in addition to group-level responses, given the large degree of variability seen in newborn infant cries (Barr, 1990; Hopkins, 2000). Finally, in light of the order effects found in Cullen et al. (1968), it is still not clear that newborn infants have enough control over their vocalizations at this point in development to demonstrate DAF effects, given the neurophysiological constraints on newborn cry production (Lieberman, 1985).

A secondary purpose of this study is to investigate age-related changes in crying during delayed and synchronous auditory feedback. As noted in the literature review above, the few studies of age-related changes in cry acoustics have produced inconsistent results. The current study will examine changes in several acoustic features of spontaneous cries of 4 and 8-week-old infants. These two time-points were selected to bracket the well-known 6-week cry peak (Brazelton, 1962). Also, while there are age-related changes in responses to DAF (Belmore et al., 1973; MacKay et al., 1968), such

studies are cross-sectional, not longitudinal. Finally, if newborn cry vocalizations are under higher levels of cortical control, rather than lower levels as traditionally assumed, then DAF effects *should* be observed within this age-period. Thus, results from this study should add to our current understanding of the neurophysiological processes that underlie newborn infant crying.

Method

Participants

Seventeen healthy newborn infants (7 males and 10 females) participated in the study. One of the 17 infants was born prematurely (36 weeks and 6 days), but was of normal birth weight. Eight infants were first-born and two infants were fraternal twins. Infants were seen twice, first at 4 weeks of age ($M=4.5$ wks, $SD=.69$, $n=16$) and again at 8 weeks ($M=7.9$ weeks, $SD=.58$, $n=17$). Fifteen infants were Caucasian and 2 infants were Asian American. Participants were recruited via email announcements sent through a university listserv and by word of mouth.

Materials

A Shure SM57 microphone was used to transmit the cries to a Marantz digital sound recorder, recording 16-bit samples at a rate of 44.1 kHz. Simultaneous and delayed auditory feedback effects were produced through software using a laptop. Two pairs of Sennheiser headphones were used; one was worn by the experimenter and the other pair was placed on the infants' ears by a second experimenter. The amplitude of the auditory feedback was measured before all visits by a sound pressure meter to ensure that sound input would be played at safe levels for the infants.

Procedure

At both 4 and 8 weeks of age, infants' spontaneous crying was recorded for 2 minutes. Most visits took place in the participants' homes, but visits for four of the infants took place in a laboratory room because it was more convenient for the parent. Visits were scheduled about 30 minutes prior to a feeding. Infants were placed in the supine position on top of a blanket resting on the floor. A microphone was placed approximately 25 centimeters from the infant's mouth, held in place by a microphone stand. The infant's parents were allowed to stay in the same room during the 2-minute recording, but were asked to keep outside of the baby's field of vision.

Once the infant began to cry, the experimenter placed a pair of headphones on the infant. A second experimenter supervised the recording equipment and initiated the delayed auditory feedback (DAF) at the correct time. The first 40 seconds of crying served as a baseline of synchronous auditory feedback, followed by 40 seconds of DAF (500 msec delay), and ending with 40 seconds of return to synchronous feedback, using a simple A-B-A design. The same procedure was followed at both visits. In addition, the mother was asked to complete the soothability sub-scale from the Infant Behavior Questionnaire (Rothbart, 1981) at the 8-week visit.

The onset and offset of each expiration during the baseline and DAF sessions was marked using Praat, a software program for acoustic analysis of speech (Boersma & Weenink, 2010). The beginning of the segment is defined at the point after each inspiration at which the waveform became noticeably higher in amplitude than the background noise. The end of the segment was defined at the point when the waveform merged into background noise before the onset of the next inspiration. Each expiratory

segment thus marked was labeled as a *cry*, a *fuss*, or *unclassified* sound. A “cry” was defined as melodic and effortful, and could be a single sound or multiple sounds interrupted by stops and pauses. A “fuss” was defined as less effortful, intense, and melodic than cry sounds. The “unclassified” sounds included coughs, grunts, or simple breathing noises.

A second coder independently listened to a random sample of 20% of the total number of cry segments. Reliability of coding was verified by calculating correlation coefficients between the primary and secondary coder for the cry count, $r = .97$, cry duration, $r = .96$, fuss count, $r = .98$, and fuss duration, $r = .98$, all of which were summed within each condition of each visit. Paired-sample t-tests were conducted to compare mean differences for the total duration and count of fusses and cries within each condition. All paired-sample t-tests were non-significant, $p > .05$.

Each cry and fuss was separately analyzed in Praat for several acoustic features (Table 1). Means and standard deviations of cries and fusses within each condition were computed for the following variables in SPSS: count, duration, fundamental frequency, energy, harmonicity, maximum frequency, and proportion of total energy in bands 1-5 (see Table 1 for definitions).

Analyses

The study followed a simple A-B-A design, with the conditions Baseline 1, DAF, and Baseline 2. Each acoustic variable for each cry and fuss sound was first characterized by its mean and standard deviation for each condition. Then, ANOVAs were conducted on, for example, the mean cry duration and the standard deviation of the cry durations in each condition. For these analyses, the sample size was 17, the number of

infants in the study. In addition, multilevel modeling was used as a second analysis strategy. Here, cry sound ($n = 1,721$ cries) was used as the unit of analysis at Level 1, and the 17 infants constituted the Level 2 units. For these models, the proportion of variability due to individual infants was first computed for each acoustic measure and then age and condition effects were added to the models as factors. Fitting these models was done using maximum likelihood estimation, and approximate F values were computed from estimates of the model parameters and covariance matrix. The hierarchical modeling strategy preserves the independently sampled unit (the infant) and provides more appropriate parameter estimates than the ANOVA approach.

Results

Simple ANOVA Results for Cry Sounds

A 2 (age) by 3 (condition) repeated-measures Analysis of Variance (ANOVA) was used to analyze the acoustic parameters of cries. No significant main effects or interactions were found for the mean and standard deviation of cry count, maximum frequency, fundamental frequency, harmonicity, or proportion of energy in frequency bands 3, 4, and 5, $p > .05$.

The only interaction between age and condition was for the standard deviation of cry duration, $F(2, 26) = 3.87, p = .034, \eta_p^2 = .230$. Post hoc analyses were conducted as recommended by Maxwell and Delaney (2000). At 4 weeks, the variability of the cry duration decreased significantly between Baseline 1 ($M = .86, SE = .14$) and DAF ($M = .67, SE = .09$), $p < .05$, but no differences were found between DAF and Baseline 2, $p > .05$. Post hoc analyses showed no significant differences between conditions among the 8-week-old infants, $p > .05$.

Age effects were only found for mean cry duration, $F(1,14) = 4.74, p = .047, \eta_p^2 = .253$ (Figure 1), and mean cry energy, $F(1, 14) = 5.01, p = .042, \eta_p^2 = .263$ (Figure 2). Mean cry duration increased between the 4-week ($M = 1.35, SE = .10$) and 8-week ($M = 1.67$ sec, $SE = .17$) visits. Mean cry energy (dB) increased between the 4-week ($M = 25.85, SE = 1.89$) and 8-week ($M = 31.43, SE = 1.83$) visits.

Condition effects were found for the proportion of energy in the lower frequency bands, particularly between the 100-500 Hz frequency band, $F(2, 28) = 3.39, p = .048, \eta_p^2 = .195$ (Figure 3), and the 500-1,000 Hz frequency band, $F(2, 28) = 3.56, p = .042, \eta_p^2 = .203$ (Figure 4). In the first frequency band (which would generally contain only the F_0), the proportion of energy in cry sounds increased significantly between Baseline 1 ($M = .022, SE = .005$) and DAF ($M = .032, SE = .009$), $p < .001$, but not between DAF and Baseline 2, $p > .05$. Similarly, the proportion of energy in the second frequency band increased between Baseline 1 ($M = .175, SE = .030$) and DAF ($M = .218, SE = .040$), $p < .01$, but did not significantly change between DAF and Baseline 2, $p > .05$.

Condition effects were also found for the standard deviation of the proportion of energy in the second (500-1,000 Hz) frequency band, $F(2, 26) = 3.46, p = .047, \eta_p^2 = .210$. Post hoc analyses showed a significant increase in the variability of energy in band 2 between Baseline 1 ($M = .017, SE = .005$) and DAF ($M = .028, SE = .009$), $p < .001$, but no differences between DAF and Baseline 2.

Multilevel Modeling of Cry Sounds

The repeated-measures ANOVAs summarized above used infants as the unit of analysis, averaging across all of the cries produced in each condition for each of the acoustic measures. As noted above, multilevel modeling may be a better approach to the

analyses, as it can model variability across infants and preserves features of each individual cry.

A series of hierarchical models was evaluated for each acoustic feature to test for improvements in fit of the model due to age, condition, and their interaction. The SPSS Mixed Models procedure was used to conduct these analyses, using a 2-level model, with random intercepts and fixed slopes. Level 1 (i) consisted of the cry sound and level 2 (j) consisted of the 17 infants. Fixed variables were age (4 weeks x 8 weeks), condition (Baseline1 x DAF x Baseline2), and the interaction of age and condition. The regression equations for both the base and test models are shown below:

$$\text{Base Model: } Y_{ij} = b_0 + u_{0j} + \varepsilon_{ij}$$

$$\text{Test Model: } Y_{ij} = b_0 + b_1(\text{age})_{ij} + b_2(\text{condition})_{ij} + b_3(\text{age} \times \text{condition})_{ij} + u_{0j} + \varepsilon_{ij}$$

Defined model terms:

Y_{ij} is the acoustic feature for cry i for infant j

b_0 is the grand mean of the acoustic feature for all cry sounds from all infants

u_{0j} is the variability of the mean of the acoustic feature for each infant, j , around the grand mean

ε_{ij} is the residual or error term

b_1 , b_2 , and b_3 are the coefficients representing the effects of age, condition, and the age by condition interaction, which are assumed to be the same for each infant

Intra-class correlations (ICCs) were computed to estimate the proportion of variance of each acoustic feature due to the individual infants. Large ICCs reflect large individual differences in the acoustic features, while small ICCs suggest that the

variability due to individual infants is small. Each acoustic feature analyzed had an ICC larger than .20 (Table 2), and most were larger than .30 (median = .39). These values indicate that a substantial portion of the variability of each acoustic feature can be attributable to individual differences among the 17 infants.

Condition effects were found for cry duration, maximum frequency, standard deviation of mean F_0 , cry energy, and the proportion of energy in the first (0-500 Hz), second (500-1,000 Hz), and fourth (1,500-2,000 Hz) frequency bands (Table 3). Post hoc analyses were conducted between Baseline 1 and DAF and between DAF and Baseline 2 using the Bonferroni correction for multiple comparisons. For all variables, significant differences ($p < .05$) were only found between 2 of the 3 consecutive conditions, mostly between Baseline 1 and DAF. Estimated marginal means and standard errors for all acoustic features are shown in Table 4.

As noted before, condition was a significant predictor for proportion of energy in the lower and upper frequency bands, which are presumably controlled by the infants' supraglottal muscles (Golub, 1980). The proportion of energy in the first frequency band increased between Baseline 1 ($M = .023$, $SE = .005$) and DAF ($M = .030$, $SE = .005$), $p = .005$ (Figure 3). Similarly, the proportion of energy in the second frequency band increased between Baseline 1 ($M = .178$, $SE = .026$) and DAF ($M = .211$, $SE = .026$), $p = .001$ (Figure 4). Last, the proportion of energy in the upper fourth bandwidth decreased between Baseline 1 ($M = .094$, $SE = .012$) and DAF ($M = .080$, $SE = .012$), $p = .011$ (Figure 5).

Condition was a significant predictor for cry maximum frequency, energy, and duration, all of which are presumably controlled by the infants' subglottal muscles

(Golub, 1980). For instance, maximum frequency decreased between Baseline 1 ($M = 1797.67$, $SE = 91.18$) and DAF ($M = 1650.27$, $SE = 90.17$), $p = .011$ (Figure 6). Cry energy also decreased between Baseline 1 ($M = 29.40$, $SE = 1.34$) and DAF ($M = 28.46$, $SE = 1.33$), $p = .059$ (Figure 7). Cry duration decreased between DAF ($M = 1.48$ s, $SE = .098$) and Baseline 2 ($M = 1.39$ s, $SE = .098$), $p = .054$ (Figure 8). Variability in mean F_0 , which is controlled by the infants' glottal muscles, decreased between Baseline 1 ($M = 72.73$, $SE = 2.88$) and DAF ($M = 68.73$, $SE = 2.86$), $p = .025$ (Figure 9).

Age was a significant predictor for cry energy, $F(1, 32.83) = 4.53$, $p = .041$.

Energy in infants' cries (db) increased between 4 weeks ($M = 25.85$, $SE = 1.89$) and 8 weeks ($M = 31.43$, $SE = 1.83$). Age did not improve model fit for any other variables, $p > .05$.

Summary of Results

The standard ANOVA results showed that the proportion of energy in the first (100-500 Hz) and second (500-1,000 Hz) frequency bands increased between Baseline 1 and DAF. Also, the variability of the proportion of energy in the second frequency band increased between Baseline 1 and DAF. The variability in cry duration decreased between Baseline 1 and DAF for the 4-week-old infants. Finally, cry duration and energy increased between 4 and 8 weeks.

Using MLM, the same significant condition effects were found for the proportion of energy in the first and second frequency bands between Baseline 1 and DAF (see Table 5). Significant condition effects were found for a number of other acoustic variables, as well, when using MLM analysis, particularly for maximum frequency, variance in mean F_0 , energy, duration, and for the proportion of energy in the fourth

frequency band (1,500-2,000 Hz). Post hoc analyses for all condition effects found in the MLM results showed significant change only between Baseline 1 and DAF conditions, which is mirrored in the ANOVA results. Although both energy and duration increased significantly between 4 and 8 weeks in the ANOVA results, only energy increased significantly between 4 and 8 weeks in the MLM results.

The Soothability Subscale of the Infant Behavior Questionnaire

Eighteen items from the Soothability subscale of the Infant Behavior Questionnaire (IBQ) were averaged into a mean soothability subscale ($\alpha = .90$). High scores indicate that parents rated their infants as highly soothable. Parents' mean soothability scores were 4.69 ($SE = .20$) out of 7 points, indicating that most parents felt their 8-week-old infants were soothable between "about half the time" (rating of 4) to "more than half the time" (rating 5). Correlations were calculated between the primary caretakers' mean soothability score and all acoustic measures (Table 6).

During the first baseline among 4-week-old infants, soothability scores were marginally negatively correlated with mean cry duration, $r(15) = -.50, p = .061$; as cry duration increased, soothability scores decreased. During the first baseline among 8-week-old infants, soothability scores were marginally positively correlated with mean harmonicity in cry sounds, $r(17) = .47, p = .06$; infants who were less soothable produced cries with more dysphonation. Soothability scores during the first baseline among 8-week-old infants were positively correlated with standard deviation of the proportion of energy in cry sounds between 1,000 and 1,500 Hz, $r(17) = .53, p = .028$, however, significance was lost when a single outlier was removed, $r(16) = .33, p = .215$.

During DAF among 4-week-old infants, soothability scores were marginally positively correlated with cry count, $r(16) = .50, p = .050$. During DAF among the 8-week-old infants, soothability scores were marginally negatively correlated with cry duration, $r(17) = -.48, p = .051$, negatively correlated with standard deviation of cry duration, $r(17) = -.51, p = .038$, and positively correlated with negative sound count (cry and fuss sounds summed), $r(17) = .73, p = .001$.

No correlations between soothability scores and any of the cry variables were significant during the second baseline among 4-week-old infants. During the second baseline (following DAF) among 8-week-old infants, soothability scores were negatively correlated with standard deviation of cry duration, $r(17) = -.49, p = .045$, and positively correlated to negative sound count, $r(17) = .57, p = .016$.

When collapsing across all three conditions at each visit, soothability scores were positively correlated with negative sound count (total number of cry and fuss sounds) among the 4-week-old infants, $r(16) = .50, p = .047$, and the 8-week-old infants, $r(17) = .63, p = .007$. No other acoustic variables were correlated with soothability scores at 4 or 8 weeks, $p > .05$.

Summary of IBQ Correlations

Soothability was only significantly correlated ($p < .05$) to variability in cry duration and frequency of negative sounds (number of cry and fuss sounds summed) among 8-week-old infants during DAF and Baseline 2 conditions. When collapsing across all conditions for each visit, soothability was positively correlated to negative sound count among 4- and 8-week-old infants. Overall, 8-week-old infants with higher numbers of negative sounds and less variability in cry duration during DAF and Baseline

2 conditions had higher soothability scores. Cry duration is marginally negatively correlated to soothability among 8-week-olds during DAF, implying that shorter cry durations are associated with more soothable infants, likely because cry sounds are not as intense.

More correlations between soothability and cry variables were found among 8-week-old infants than 4-week-old infants; this is reasonable given the fact that the IBQ was administered to parents when infants were 8-weeks-old. The highest number of correlations was found among 8-week-old infants during the DAF condition; infants who had more frequent negative sounds, and shorter and less variable cries had higher soothability scores, however, it is not clear the degree to which infants' responses to DAF is influencing this correlation.

Discussion

The effects of DAF on infant crying are subtle and partly determined by the method of analysis employed. When using the 17 infants as the unit of analysis and comparing average acoustic parameters across conditions, DAF effects on cry sounds were only seen for mean proportion of energy in bands 1 and 2 and for the variability in proportion of energy in band 2. Post hoc analyses indicate significant differences only between Baseline 1 and DAF for these effects. The only interaction effect found in these ANOVAs was for the standard deviation of cry duration; the variability of cry durations significantly decreased between Baseline 1 and DAF conditions, but only for 4-week-old infants.

When analyzing individual cry sounds as level 1 units in multilevel modeling, additional effects of DAF on cry sounds were found, specifically for cry duration,

maximum frequency, variability of the mean F_0 , energy, and the proportion of energy in frequency bands 1, 2, and 4. Post hoc analyses indicated, again, significant differences between Baseline 1 and DAF conditions.

Cullen (1968) found that cry duration decreased during DAF, regardless of test-order. Also, cries decreased in amplitude, but only when infants were tested in the order for which DAF occurred first. However, no further acoustic analyses were conducted in Cullen's study. The current study did show DAF effects on cry duration and cry energy, but only in the MLM analyses. Thus, both the current study and previous research suggest that DAF influences the duration of crying as well as the energy of the cry. Both studies, though, indicate that order of conditions appears to influence cry sounds in addition to effects of DAF.

Very few age effects were found in the current study, which followed a short-term longitudinal design with testing at both 4 and 8 weeks. For the infants-as-units ANOVA analyses, cry duration increased and cry energy increased between infants' 4- and 8-week visits. For the cries-as-units MLM analyses, only cry energy increased between infants' 4- and 8-week visits. Few studies to this date have focused on the developmental changes in cry acoustics during the infants' first year; such studies typically emphasize changes in the mean F_0 of infants' cry sounds and thus do not fully capture the extent to which age effects are present, especially within the first three postnatal months. A number of cry studies using healthy, full-term infants have not observed any age-related changes for cry mean F_0 between the ages of 1- to 3-months (Baeck & de Souza, 2007; Lind & Wermke, 2002; Murry et al., 1983). Similarly, in the current study, no age effects were found for mean F_0 or its variability. Thus, denser time-sampling, longer age spans,

and more extensive acoustic analyses are needed to determine if there are any changes in cry sounds during these early months.

Cry sounds within a single infant should not be considered as independent observations; however, this is one of the key assumptions for the analyses typical in this literature. MLM analyses allow for dependent observations, as data are treated as hierarchical. Also, when analyzing cry acoustics, inter-individual variability is highest during the first three months of life (Barr, 1990; Hopkins, 2000), increasing the likelihood that the homogeneity of variance assumption is violated when using ANOVA analyses in cry studies. In contrast, MLM analyses can model variability across infants through the use of varying regression parameters. Finally, valuable data are lost when acoustic measures relating to cry sounds are averaged for a single infant. MLM analyses measure individual-level responses to independent variables, which is especially important when effects of such variables are unknown in the literature and when variability within infants is large. Thus, MLM analyses are the more appropriate tools for infant cry studies analyzing several sounds from a relatively large number of infants. To our knowledge, this study is the first to use MLM analyses in the acoustic analysis of cry sounds.

There were a few significant correlations between infants' soothability ratings and their frequency of negative (fuss and cry) sounds or their cry duration. Interestingly, there were more significant or near-significant correlations between soothability and frequency or duration of crying among 8-week-old infants. There are several possible explanations, but one likely reason for this change is that mothers' perception of their infants' temperament is only just crystallizing in the first 2 months (Rothbart & Bates, 2006). It seems likely that basic information about their infants' cries (e.g., frequency

and duration) might be influencing mothers' developing temperament characterizations. Perhaps previous studies that have linked early cry measures to later outcomes can be at least partially explained by a mediating effect of infant temperament.

If crying should be considered a graded signal, then the infant's level of arousal should directly affect the acoustic characteristics of their cry sounds. A number of studies support this, as cry characteristics have been linked to infants' level of distress, rather than to specific contexts, like hunger or pain (i.e., Green et al., 1998; Lester & Zeskind, 1982; Porter et al., 1986). There are also differences in the arousability of infants, as seen when comparing healthy infants to infants with CNS deficits (Karelitz et al., 1964) and among "colicky" infants (Barr & Gunnar, 2000).

Beyond individual differences, infants' current state of arousal can contribute to the initiation, intensity, and duration of their cry bouts. This fact has direct consequences in the current study, as infants' initial states of arousal were not necessarily uniform across infants, although the fact that recording did not begin until infants were crying steadily should ameliorate this. However, some infants appeared to calm down during the middle of the cry recording, whereas other infants grew increasingly more distressed throughout the recording. It is not clear whether DAF effects can be observed across all levels of arousal. Infants may not respond to changes in feedback when in a highly aroused state, as they may not be closely attending to auditory stimuli when highly distressed. Because infants' arousal levels likely intensify throughout a cry bout, their responsiveness to DAF may be dependent on their level of distress.

In studies, such as this one, that use a standard ABA design, the infants' arousability is certainly a potential confound. A standard threat to validity of these

designs is ‘historical’ change, which in this case would mean changes in arousal levels, albeit over a relatively brief interval of crying. Although the hypotheses related to DAF predicted several U-shaped effects on cry acoustics, in many cases, the overall trend was linear or only showed a significant difference between DAF and one of the baseline conditions. Despite these patterns, it is difficult to attribute the differences between DAF and one of the baselines solely to differences in arousal. There is no *a priori* reason why cry acoustics should shift systematically after 40 seconds of crying in the first baseline, or after 80 seconds of crying (i.e., the end of DAF). In fact, there is a critical need for detailed studies of changes in cry acoustics during long cry bouts in order understand how arousal relates to cry acoustics (Green, Gustafson, Irwin, Kalinowski, & Wood, 1995; Green, Gustafson, & McGhie, 1998).

Future studies of DAF might yield clearer results if the ABA design were replaced with other manipulations. One possibility would be to alter the feedback during DAF itself, for example, by altering pitch of the cry feedback or using white noise as the delayed feedback. If cry acoustics change differently in response to DAF of unmanipulated crying than to DAF of altered crying or white noise, the argument that higher brain centers are involved in the production of crying would be strengthened.

Historically, researchers presumed acoustic characteristics of cry sounds to be under primary control of lower-level CNS functions, linked to respiratory movements in particular. If the condition effects observed here are explained as infants’ responses to DAF, then newborn cry sounds may be under greater cortical control than previously assumed. High variability observed between infants suggests that some infants may be more responsive to DAF than others; infants most responsive to DAF may have higher

levels of cortical control over their cry sounds. Collecting several samples from individual infants may reveal that DAF responses are a function of increased cortical control over cry sounds, which may not necessarily occur at consistent ages between infants, possibly explaining why so few age effects were found in the current study.

If early cry acoustics can be linked to later outcomes, as found in studies conducted by Karelitz et al. (1964), Lester (1987), and Wermke et al. (2002), the question raised is whether such correlations are primarily explained by differences in cortical control over cry sounds, or whether these differences are a result of the infants' interactions with their environment during cry bouts. For example, there are a number of studies that link vagal tone (heart rate variability) to later social skills and emotion regulation (Porges et al., 1994; Porges, Doussard-Roosevelt, Portales, & Greenspan, 1996). Higher social skills could lead to better cognitive, language, and emotional outcomes. Thus, in addition to temperament as a possible mediator of the relation between early crying and later outcomes, it would appear that basic CNS maturity or functioning might serve a similar role.

The auditory and kinesthetic feedback received during cry bouts may enhance infants' experiences in perception-action coupling, a necessity for later speech production (Hopkins, 2000). Changing typical auditory feedback during cry bouts allows us to examine the role of auditory feedback on young infant cry production, and evaluate whether infants are able to self-organize when auditory feedback is no longer synchronous. Infants that have ample experiences in perception-action coupling may more quickly perceive and react to changes in feedback than infants who are still developing skills in perception-action coupling. It could be suggested that the infants

who are able to alter their cry sounds during DAF are the infants who are more advanced in perception-action coupling. To extend this idea, it is possible that infants most responsive to DAF may produce their first words earlier in development. Longitudinal follow-up studies are needed in order to evaluate this claim.

Given the degree of variability seen between infants in this study, other measures of arousal, such as heart rate variability, cortisol levels and even brain imaging, should be combined along with cry acoustics to more accurately determine infants' responses to delayed auditory feedback. Also, it is important to differentiate whether infants' responses are specific to self-feedback versus auditory feedback in general (from white noise or other infant cries, for example). Furthermore, it would be beneficial to observe infants' responses to DAF during cry bouts in atypical populations, such as in hearing-impaired infants, infants with Williams Syndrome, and even in premature or low birth-weight infants.

In sum, this study showed that newborn infants' cries may be affected by DAF, however, their responses are not consistent, nor are they necessarily seen within each infant. A large part of this may be due to the lack of control infants have over their vocal tract at this age (4 and 8 weeks), which occurs before the many physiological changes that take place for the infant around 3 months of age (Emde et al., 1976; Lieberman, 1985). In the future, measuring infants' limb movements during crying with and without delayed auditory feedback would give us more information on whether infants' motor movements during cry bouts are affected by changes in their auditory feedback.

To close, the exact role auditory feedback plays in later language development, and its role in cry production, is still unclear, especially given the inconsistencies in the

DAF literature for infants and children. Given the number of condition effects seen in the current study, along with the high variability observed within and between infants, it is reasonable to assume that DAF does affect young infant crying. However, there is no particular way in which infants *should* respond during DAF. While some infants may have higher pitched cry sounds during DAF compared to baseline conditions, other infants may have lower pitched cry sounds during DAF. The fact that infant responses to DAF are variable thus emphasizes the need for researchers to analyze individual, rather than group-level responses, as achieved through use of MLM. Infants' early responses to DAF may better inform us about the neurophysiological processes that underlie newborn cry production and thus help determine the role of early crying in later cognitive and language development.

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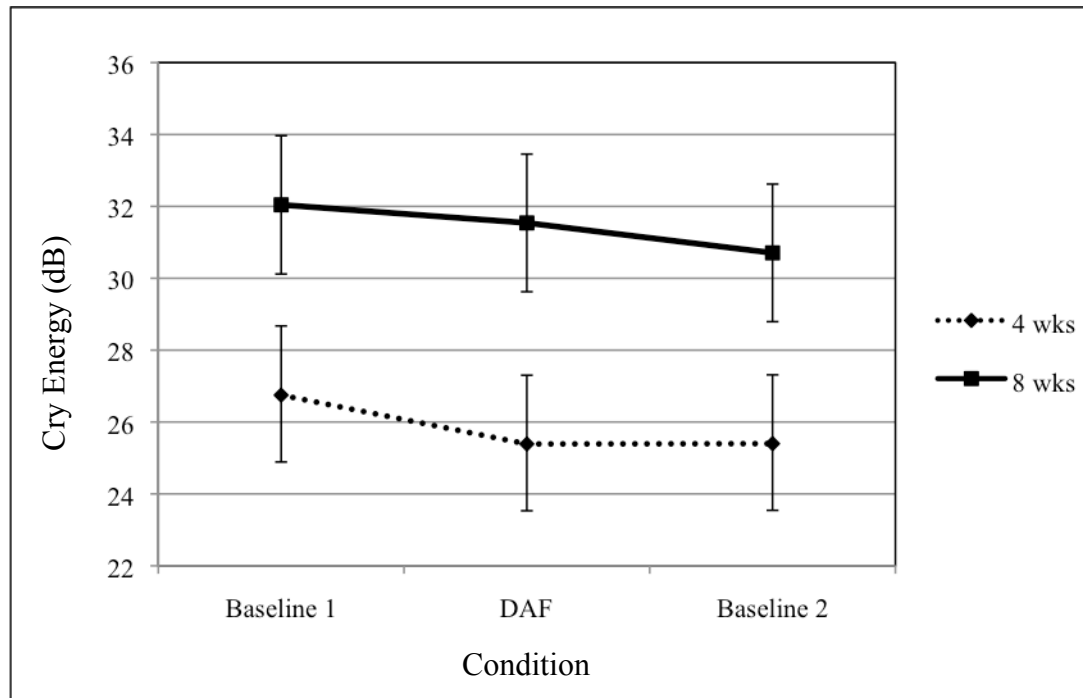


Figure 1. Age effects on mean energy in cry sounds.

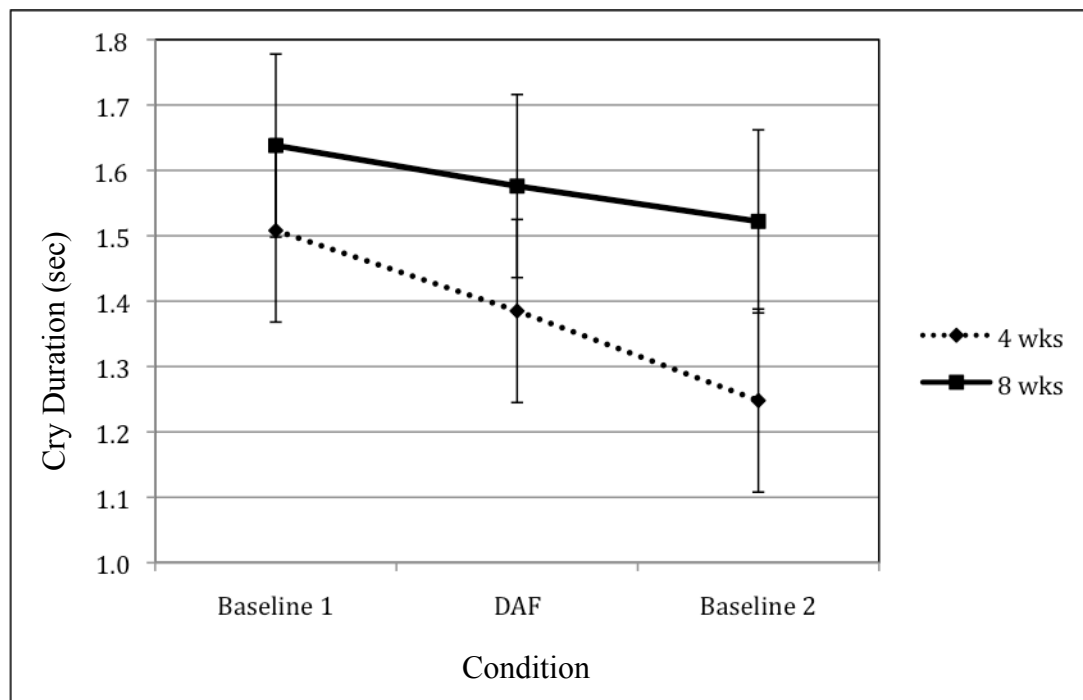


Figure 2. Age effects on mean cry duration.

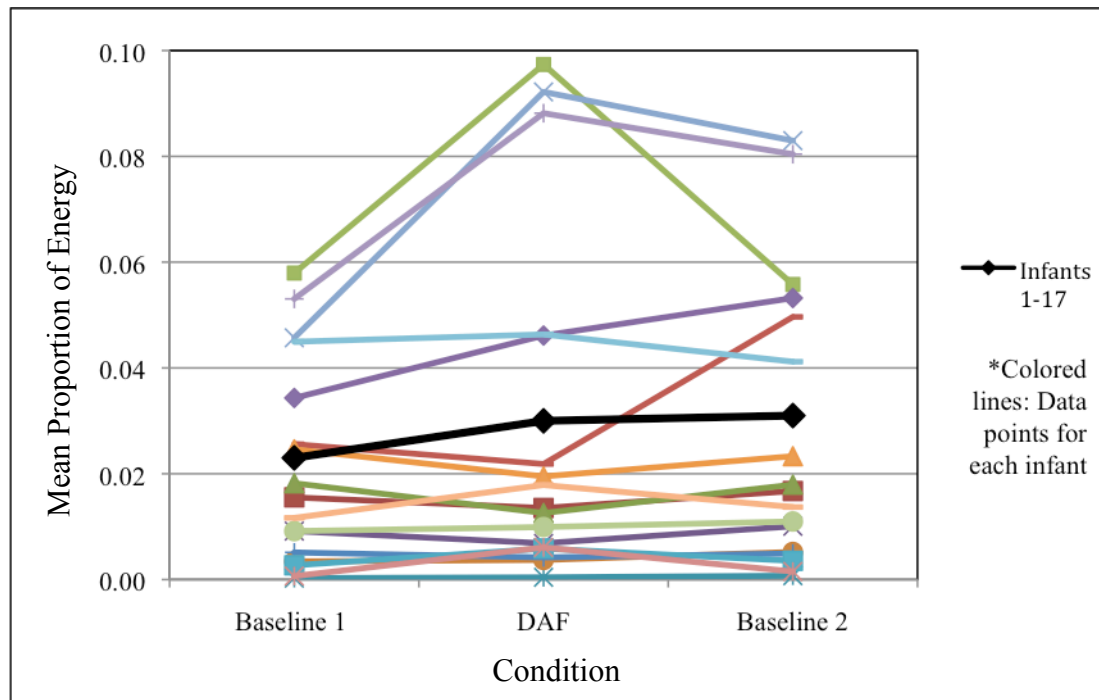


Figure 3. DAF effects on mean proportion of energy in the 100-500 Hz band.

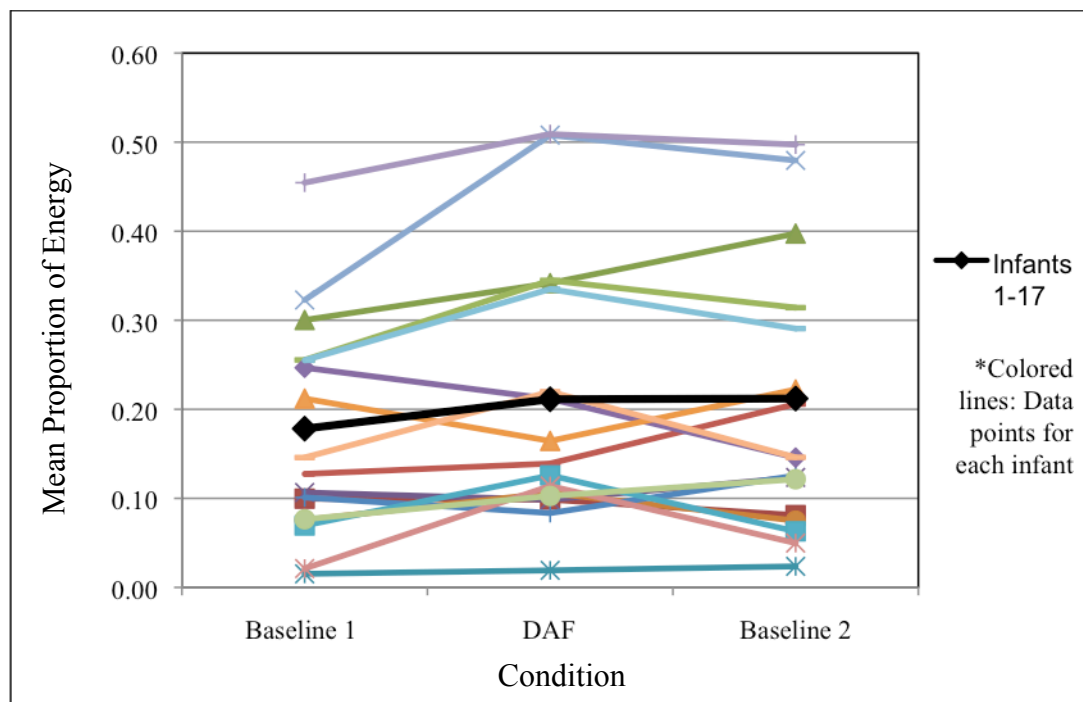


Figure 4. DAF effects on mean proportion of energy in the 500-1,000 Hz band.

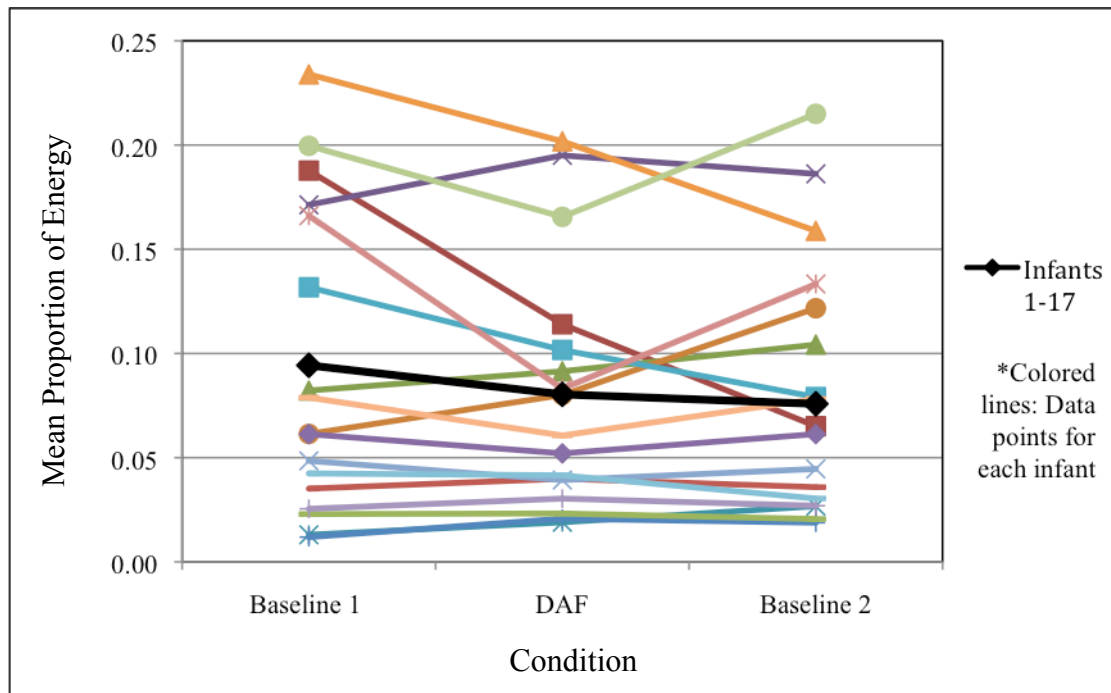


Figure 5. DAF effects on mean proportion of energy in the 1,500-2,000 Hz band.

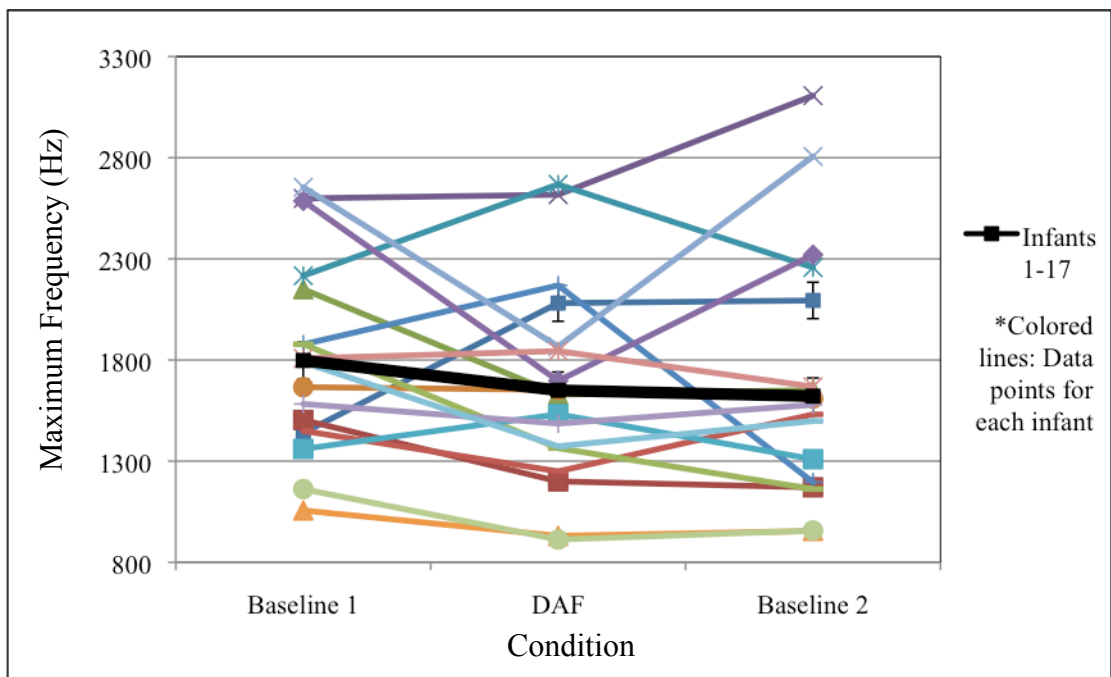


Figure 6. DAF effects on mean maximum frequency of cry sounds.

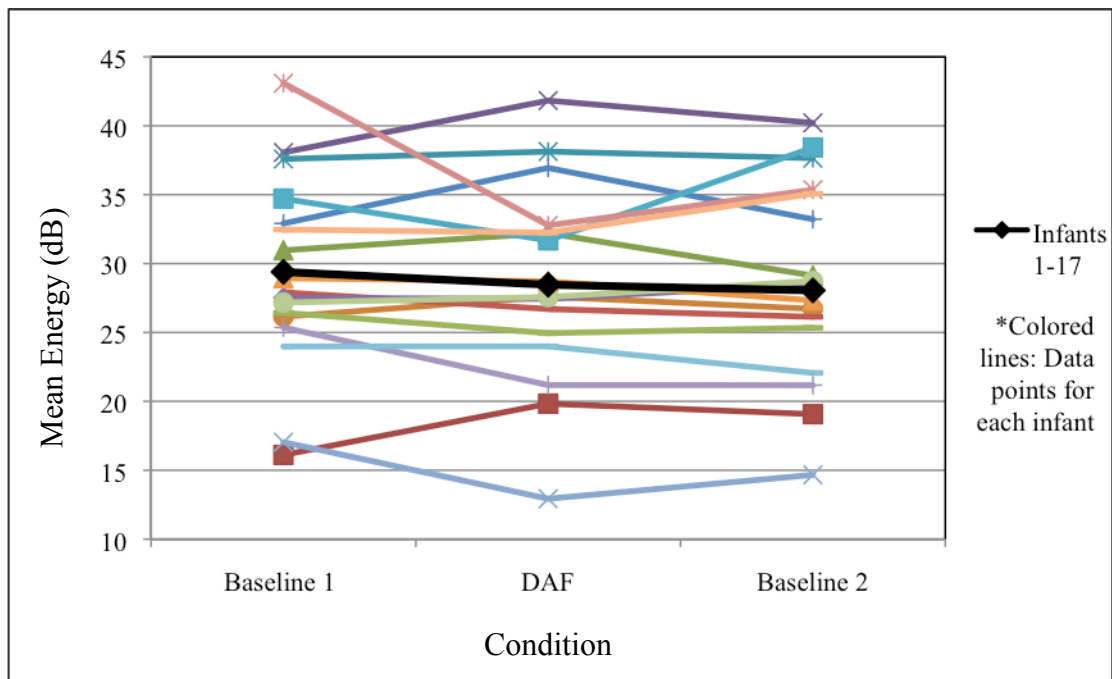


Figure 7. DAF effects on mean energy in cry sounds.

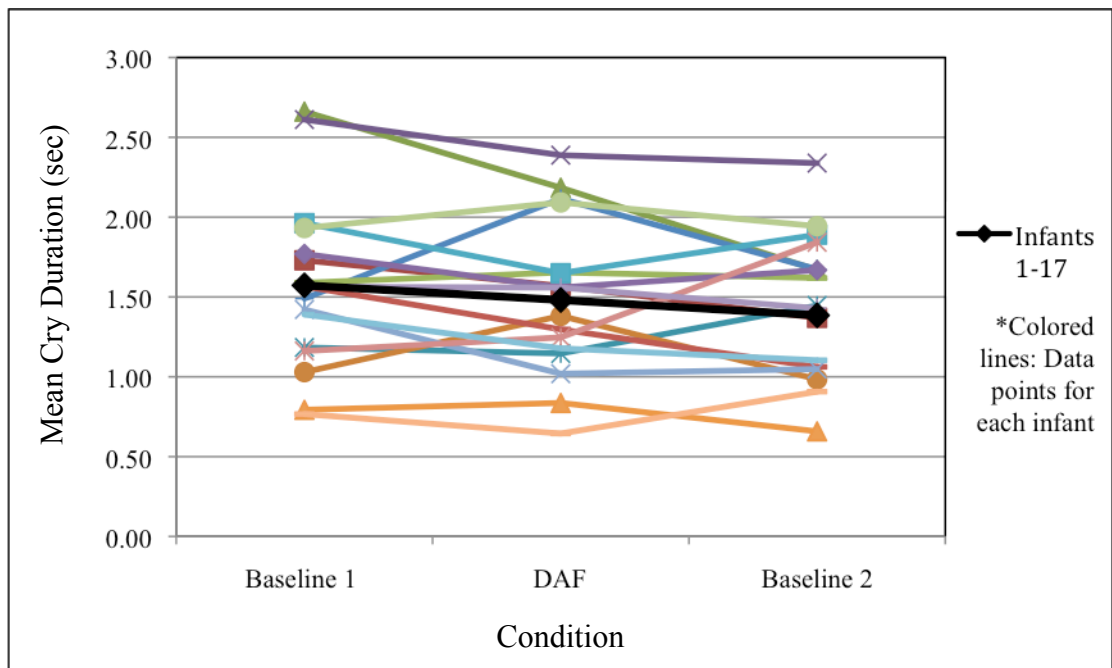


Figure 8. DAF effects on mean cry duration.

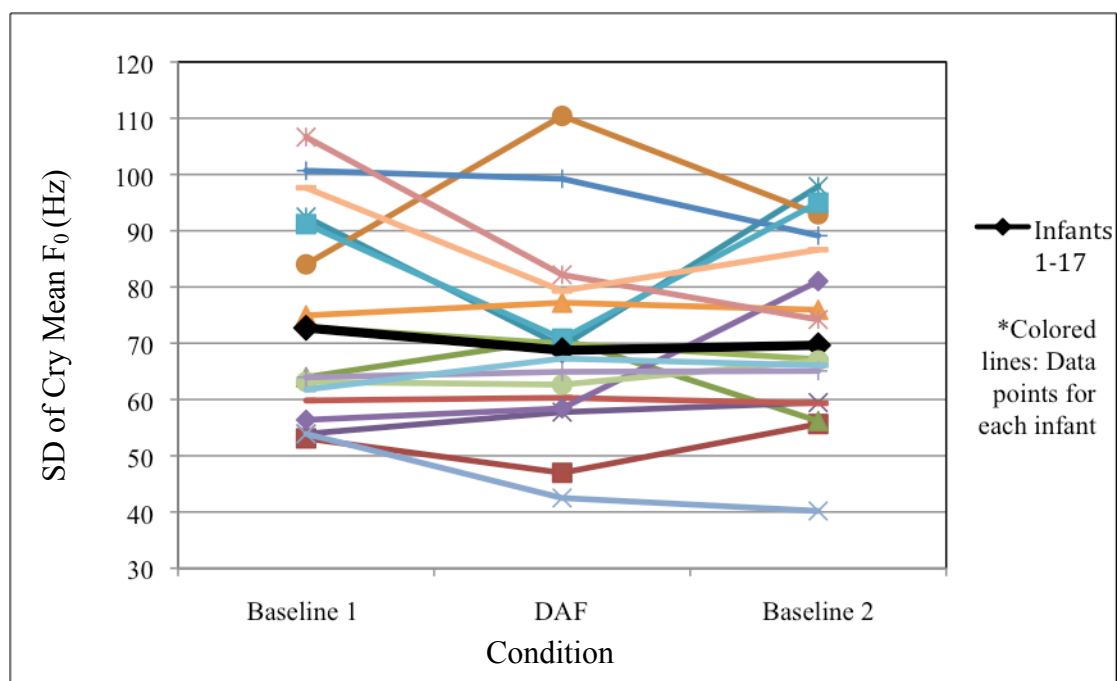


Figure 9. DAF effects on the mean variability in cry mean F_0 (Hz).

Table 1

Definitions of Acoustic Measures

Count	Number of expiratory segments labeled cry or fuss
Duration	Time from beginning to end of each expiratory segment (in msec).
Fundamental Frequency	Mean and SD of the extracted pitch trace for the entire vocalization, estimated using an autocorrelation method with the pitch range set at 200-700 Hz.
Energy	Sum of the squared amplitudes of the time sampled vocalization. Energy scores have been converted into decibel (dB) units.
Maximum Frequency	The frequency in the long term average spectrum with the greatest amplitude (in Hz).
Spectral Energy	The energy in selected frequency bands from the long term average spectrum of each cry or fuss. Expressed as a proportion of the total energy. Band1= 100-500Hz, Band2= 500-1000Hz, Band3= 1000-1500Hz, Band4 = 1500-2000Hz, and Band5 = 2000-2500 Hz.
Harmonicity	The degree of acoustic periodicity, expressed in dB. The larger the value, the more periodic the cry or fuss, with less time spent in dysphonation or unusual phonatory segments

Table 2

Intra-class Correlations (ICCs) for MLM Models on Cry Sounds

	ICC
Duration M (s)	0.35
Max. Freq. (Hz)	0.22
Mean F_0 (Hz)	0.54
SD Mean F_0 (Hz)	0.27
Energy (db)	0.56
Harmonicity (db)	0.41
Prop. Band 1 (Hz)	0.38
Prop. Band 2 (Hz)	0.44
Prop. Band 3 (Hz)	0.22
Prop. Band 4 (Hz)	0.38
Prop. Band 5 (Hz)	0.40

Table 3

Condition Effects from Multilevel Modeling Analyses

Variables	<i>df</i>	<i>F</i>	<i>p</i>
Duration (s)	2, 1691.2	8.79**	.000
Max. Frequency (Hz)	2, 1692.6	6.27**	.002
Mean F ₀ (Hz)	2, 1689.6	0.48	.622
SD Mean F ₀ (Hz)	2, 1693.2	3.71*	.025
Energy (db)	2, 1689.7	5.13**	.006
Harmonicity (db)	2, 1691.3	1.57	.208
Prop. Band 1 (Hz)	2, 1691.6	6.79**	.001
Prop. Band 2 (Hz)	2, 1690.5	8.02**	.000
Prop. Band 3 (Hz)	2, 1694.6	1.71	.182
Prop. Band 4 (Hz)	2, 1691.2	7.36**	.001
Prop. Band 5 (Hz)	2, 1691.1	0.00	.997
* <i>p</i> < .05 ** <i>p</i> < .01			

Table 4

Estimated Marginal Means (SEs) by Condition at 4 and 8 Week Visits for Cry Sounds

Variables	4 weeks			8 weeks		
	B1	DAF	B2	B1	DAF	B2
Count	16.68 (2.51)	20.19 (2.33)	20.19 (3.03)	15.69 (2.38)	16.50 (2.22)	16.88 (2.34)
Duration <i>M</i> (s)	1.51 (0.14)	1.39 (0.14)	1.25 (0.14)	1.64 (0.14)	1.58 (0.14)	1.52 (0.14)
Max. Freq. (Hz)	1745.34 (131.20)	1653.30 (129.10)	1540.84 (128.90)	1850.01 (126.66)	1647.25 (125.93)	1701.99 (125.59)
Mean F_0 (Hz)	399.42 (12.53)	397.69 (12.47)	397.88 (12.47)	404.53 (12.12)	403.00 (12.10)	400.76 (12.09)
SD Mean F_0 (Hz)	71.84 (4.15)	64.44 (4.10)	66.73 (4.09)	73.61 (4.01)	73.02 (3.99)	72.56 (3.98)
Energy (db)	26.75 (1.92)	25.39 (1.91)	25.40 (1.91)	32.04 (1.86)	31.54 (1.86)	30.71 (1.86)
Harmonicity (db)	11.38 (0.86)	11.95 (0.85)	11.27 (0.85)	12.16 (0.83)	11.63 (0.83)	11.59 (0.83)
Prop. Band 1 (Hz)	0.029 (0.008)	0.034 (0.008)	0.034 (0.008)	0.017 (0.007)	0.026 (0.007)	0.028 (0.007)
Prop. Band 2 (Hz)	0.176 (0.037)	0.219 (0.037)	0.214 (0.037)	0.180 (0.036)	0.204 (0.036)	0.210 (0.036)
Prop. Band 3 (Hz)	0.229	0.242	0.262	0.215	0.205	0.212

	(0.022)	(0.021)	(0.021)	(0.021)	(0.021)	(0.021)
Prop. Band 4 (Hz)	0.083	0.078	0.069	0.105	0.083	0.083
	(0.017)	(0.017)	(0.017)	(0.016)	(0.016)	(0.016)
Prop. Band 5 (Hz)	0.085	0.088	0.086	0.097	0.094	0.096
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)

Note. B1 = first baseline, DAF = Delayed Auditory Feedback, B2 = second baseline

Table 5

Simple ANOVA analyses compared to MLM analyses for Cry Sounds

Variables	ANOVA	MLM
Duration (s)	age effect	condition effect ²
SD Duration (s)	interaction effect ^{1; 4wks}	-----
Max. Frequency (Hz)	no effects	condition effect ¹
Mean F ₀ (Hz)	no effects	no effects
SD Mean F ₀ (Hz)	no effects	condition effect ¹
Energy (db)	age effect	age and condition ¹ effects
Harmonicity (db)	no effects	no effects
Prop. Band 1 (Hz)	condition effect ¹	condition effect ¹
Prop. Band 2 (Hz)	condition effect ¹	condition effect ¹
SD Prop. Band 2 (Hz)	condition effect ¹	-----
Prop. Band 3 (Hz)	no effects	no effects
Prop. Band 4 (Hz)	no effects	condition effect ¹
Prop. Band 5 (Hz)	no effects	no effects

Note. SD variables that average across cries in each condition cannot be included in MLM analyses. Only SD variables that produced significant effects are included in table.

¹ Post hoc analyses showed significant differences only between Baseline 1 and DAF.

² Post hoc analyses showed only marginally significant differences between DAF and Baseline 2.

Table 6

Correlations between Soothability Scores and Acoustic Variables at 4 and 8 weeks

Age	Condition	Acoustic Variable	<i>r</i>
4-Weeks	Baseline 1	Mean Cry Duration	-.50 [†]
	DAF	Cry Count	.50 [†]
	Entire Cry Bout	Negative Sound Count	.50 ^{**}
8-Weeks	Baseline 1	Mean Harmonicity	.47 [†]
		SD Prop Band 3	.53 ^{*a}
	DAF	Mean Cry Duration	-.48 [†]
		SD Cry Duration	-.51 ^{**}
		Negative Sound Count	.73 ^{***}
	Second Baseline	SD Cry Duration	-.49 ^{**}
		Negative Sound Count	.57 ^{**}
	Entire Cry Bout	Negative Sound Count	.63 ^{**}

Note. “Entire Cry Bout” was computed by averaging the number of fuss and cry sounds across all three conditions (Baseline 1, DAF, and Baseline 2).

[†] $p < .10$

^{**} $p < .05$

^{***} $p < .01$

^a $p > .05$ when single outlier is removed